Constraining the post-emplacement evolution of the Hebridean Igneous Province (HIP) using low temperature thermochronology: How long has the HIP been cool?

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Abstract

The thermal history of the Hebridean Igneous Province has been determined through the application of low-temperature thermochronology to the four central complexes in the province. The zircon (U-Th)/He age (59.4 ± 3.3 Ma, 1σ, n=18) and the ages from each complex (60.7 ± 2.3 Ma Skye; 58.0 ± 0.4 Ma Mull; 55.9 ± 3.2 Ma Ardnamurchan; 55.6 ± 2.7 Ma Rum) are indistinguishable from the crystallization ages. Apatite fission track ages (61.2-57.2 Ma, mean of 59.3 ± 3.4 Ma) from the major plutonic units also overlap crystallization ages, implying that on a regional scale, the Hebridean Igneous Province cooled rapidly to near surface temperatures immediately after emplacement. However, apatite fission track ages and track lengths and apatite (U-Th)/He ages from some small volume intrusions in the Skye and Rum central complexes identify localised mid-Eocene (45-47 Ma) cooling. Forward and inverse modelling suggests a discrete heating-cooling event at ~ 47 Ma, which may have been caused by structurally-controlled localised advection of heat above shallow emplacement. This is the first suggestion of Eocene magmatism in the Hebridean Igneous Province

Although the processes controlling the emplacement of Large Igneous Provinces are usually well known (see review by Coffin & Eldholm 1994), many aspects of their evolution are poorly understood.. The distribution and timing of uplift and denudation associated with syn- and post-emplacement tectonic processes is poorly quantified (Bryan *et al.* 2002). The denudation of the youngest volcanic units often restricts quantification of the original volume and extent of the province (Bryan *et al.* 2002; Saunders *et al.* 2007) and the absence of suitable chronometers rules out determining the duration of hydrothermal activity.

Understanding the post-emplacement evolution is vital if the thermal evolution of LIPs, the formation of associated ore bodies, and regional tectonic processes are to be determined. In recent years the combination of low temperature thermochronometers, in particular the apatite and zircon fission track and (U-Th)/He thermochronometers, have been exploited to quantify the advection of rocks though isothermal surfaces (Brown *et al.* 1994; Gleadow & Brown 2000; Kohn *et al.* 2005; Spotila 2005; Stockli 2005; Dobson *et al.* 2009). In shallow plutonic systems where ambient crustal temperatures are low, thermochronology can be used to constrain the movement of isothermal surfaces though cooling magmatic bodies and the thermally-overprinted country rocks (e.g. Lewis *et al.* 1992), as well as to quantify denudation associated with underplating-driven uplift (Pik *et al.* 2003; Persano *et al.* 2007).

The Hebridean Igneous Province (HIP) is one of the earliest magmatic sub-provinces in the North Atlantic Igneous Province. It lies along the west coast of Scotland, covering large areas of the Inner Hebridean islands, and extends onto the adjacent mainland (Fig. 1 & 2A). High precision U-Pb and ^{40}Ar-^{39}Ar dating constrains igneous activity to 61.2-55.7 Ma (Pearson *et al.* 1996; Chambers & Pringle 2001; Chambers *et* *al.* 2005) (Fig. 2B). Although the HIP has been fundamental in the development of modern igneous geology (Harker 1904; Richey 1935), the late-stage evolution of the volcanic-hydrothermal system, and the timing, volume, rate and distribution of denudation during the unroofing of the plutonic complexes is largely unknown. This limits our understanding of the regional tectonic processes controlling this section of the Atlantic margin and the role of the onshore volcanics as a source region for the surrounding basins. The tight temporal constraint on emplacement-eruption and the absence of significant post-Palaeogene modification makes the HIP well suited to investigation using low temperature thermochronology. In this study we use new apatite and zircon (U-Th)/He (AHe and ZHe) and apatite fission track (AFT) analyses from the plutonic complexes of the HIP to produce detailed thermal histories in order to resolve the complexities of the post-magmatic evolution.

Geological background of the HIP

The majority of the HIP formed by the rapid eruption of three large flood-basalt lava fields at 61-60 Ma (Fig. 2). Sedimentary rocks deposited during hiatuses in the fissure eruptions, the palaeo-topography buried by the flood basalts, and the cross-cutting relationships between intrusive and extrusive units indicate that localised erosion occurred prior to, and during the main fissure-fed eruptions (Fig. 2). At ~59 Ma, central volcanic superstructures developed on Mull, Skye and Ardnamurchan (Fig. 2). The associated sub-volcanic plutonic systems, exposed today as central complexes, were emplaced 2-4 km below the basaltic lava piles (Williamson & Bell 1994; Emeleus & Bell 2005). Intense high temperature (>500°C) hydrothermal activity extended up to 10 km from the complex margins on Mull and Skye (Forester & Taylor 1976; Valley & Graham 1996; Monani & Valley 2001), though little activity is recorded on Rum and at Ardnamurchan (Holness 1999; Holness & Isherwood 2003). Post-magmatic denudation of the central volcanic edifices is thought to have been rapid, occurring immediately after the cessation of volcanism (see review in Brown *et al.* 2009). The shallow emplacement level, rapid pre- and syn-magmatic erosion, and large convective hydrothermal systems suggest rapid advection of heat and the cooling of the plutonic units to ambient, near surface temperatures soon after the cessation of magmatic activity (Taylor & Forester 1979).

The extrusive units associated with central complexes are poorly preserved (Fig. 2), and the original volumes are unconstrained. Remobilisation of the offshore sedimentary sequence prevents mass balance calculations, as Palaeogene sediments derived from the HIP are indistinguishable from the volumetrically-dominant Palaeogene material sourced from elsewhere in the North Atlantic Igneous Province (White & Lovell 1997; Jones *et al.* 2002). It has been proposed that pulses of clastic fan deposition in the North Sea, Faroes-Shetland and Porcupine basins correlate with regional scale pulses of shallow level emplacement, implying a close temporal relationship between magmatic and surface processes (White & Lovell 1997). The rapid fall in rates of fan deposition from peak sediment supply at 59 Ma, suggests that the majority of denudation in the HIP had occurred by this time (Fyfe *et al.* 1993; Nadin *et al.* 1995; White & Lovell 1997; Jones *et al.* 2002).

Previous efforts to quantify the cooling history of the HIP are limited to a pioneering fission track study of the Skye Central Complex and the surrounding country rocks (Lewis *et al.* 1992). Country rocks close to the contact have AFT ages as young as 47.0 ± 3.3 Ma, and the effect of the thermal overprint decreases systematically to a distance of ~ 10 km from contact. However, the fully annealed country rocks have a mean AFT length of 13 µm and track length distributions that are inconsistent with samples that have cooled rapidly following an overprint event in a near surface thermal aureole (Fig. 3A). Zircon fission track (ZFT) ages from the plutonic units range from 45.8 ± 4.3 Ma to 53.1 ± 3.7 Ma and show no trend with the crystallization age of the pluton (Lewis *et al.* 1992). The data require rapid cooling from 250ºC to 70ºC approximately 10 Myr after pluton emplacement. Lewis *et al.* (1992) argue that the mid-Eocene AFT and ZFT ages and the short fission track lengths require either long-lived (i.e. slow cooling) or re-invigorated (i.e. late-stage intrusion) convective heat flow from depth along "thermal funnels" (Taylor & Forester 1971).

Quantifying the thermal evolution of the HIP

To test which of these the competing cooling models can generate the ZFT and AFT data of Lewis *et al.* (1992) we have used a finite element thermal model (Heat 3D, Wohletz & Heiken 1991) to quantify the cooling of the Skye and Rum central complexes. Modelling cooling without denudation or hydrothermal activity suggests that thermal re-equilibration of the upper 5 km is rapid, and would be complete within 2-3 Myr of emplacement (Fig. 3). Therefore all plutonic units should yield ages that are indistinguishable from crystallization ages for all dating techniques. The predicted cooling estimates are highly conservative, given the known extensive hydrothermal activity and syn-magmatic denudation however; poor understanding of the timing, volume and duration of both hydrothermal activity and denudation prevents their inclusion and further refinement of the model. The models also constrain the sensitivity of low temperature thermochronology to different thermal and tectonic scenarios, as low temperature thermochronology will only be able to identify denudation driven cooling events if denudation occurs after the samples have reached ambient crustal temperatures (i.e. > 3 Myr after emplacement).

This simplified modelling shows that even in the absence of a hydrothermal system (i.e. an end-member slow-cooling scenario) the AFT and ZFT data require either continuous emplacement from 60-45, or a phase of major emplacement at 50-47 Ma (on the scale of the entire complex). Neither scenario is supported by field evidence.

Methodology

Samples were chosen to span the full temporal range of intrusion at each complex. Where possible, intrusions with independent age constraints (U-Pb, $^{40}Ar/^{39}Ar$ and ZFT) were analysed. The localities are listed in Tables 1-3. Apatite and zircon were separated using standard magnetic and density separation techniques, and additional zircons were picked from the small volume aliquots remaining after U-Pb analyses (Hamilton *et al.* 1998; Chambers & Pringle 2001; Monani & Valley 2001).

Inclusion- and defect-free crystals were hand picked for He dating under a 500x binocular polarising microscope, and the geometry and dimensions of each crystal recorded. Crystals were packed into Pt-foil tubes (zircon) or stainless steel capsules (apatite), and degassed using a double-walled resistance furnace (Persano *et al.* 2002). Some multi-crystal aliquots were prepared to minimise the effect of the low U and Th concentrations found in most HIP apatite and zircon. After degassing, samples were spiked with ^{235}U and ^{230}Th, dissolved using standard procedures and U-Th determinations made using a VG PQ2plus ICP-MS (Balestrieri *et al.* 2005; Foeken *et* *al.* 2006; Dobson *et al.* 2009). Age uncertainties for mean (U-Th)/He ages were calculated from the 1σ sample specific age reproducibility unless otherwise stated.

The number of suitable apatites in many samples was limited by small (< 1 μm) fluid inclusions. Apatites in sample SK4 contained numerous highly acicular monazite crystals (< 3 μm diameter). To monitor the effect of inadvertently analysing monazite-bearing apatite, a monazite (< 10 μm long, 1-2 μm diameter) inclusion-bearing apatite aliquot was analysed (SK4-6).

Zircons from the volcaniclastic Muck Tuff were used as an internal age standard (Table 1), as the ZHe age (58.7 ± 1.6 Ma n=6 (1σ); Dobson *et al.* 2009) is within error of zircon U-Pb age (61.15 ± 0.25 Ma; Chambers *et al.* 2005) from the same aliquot. Strong U and Th zonation in zircon can have a significant effect of the fractional loss of He by α-ejection (Hourigan *et al.* 2005; Dobson *et al.* 2008), and assuming homogeneity can lead to over- or under-estimation of ZHe ages. U and Th zonation was assessed using cathodoluminescence (CL) intensity (Corfu *et al.* 2003; Dobson *et al.* 2008) which has been shown to vary systematically with U and Th concentration in some HIP zircons (Dobson 2006). Although this relationship has not been quantified in all samples the U and Th concentrations and CL intensity variation in all samples are comparable. The CL zoning observed within each sample was used as a first-order proxy for U and Th zonation to assess the error introduced by applying the conventional α-ejection (F_T) correction (Dobson 2006; Dobson *et al.* 2009).

Apatite fission track analyses were determined using the external detector method (Hurford & Green 1982), following procedures described in Persano *et al.* (2005). All samples apart from SK4 have very low U concentrations, and spontaneous track densities of ~$1x10^5 cm^{-2}$, leading to large 1σ uncertainties on many of the AFT ages. Uranium zonation in apatites was assessed from the fission track mounts, and was negligible in all but two samples (R11 and ML5). Low apatite yields, and low track densities prevented measurement of track length distributions in many samples, and Cf irradiation (Donelick & Miller 1991) failed to increase confined track numbers significantly. Track lengths discussed below are from mounts that were not Cf irradiated.

Results

Mull & Ardnamurchan

ZHe thermochronometry was performed on euhedral zircons from two plutonic samples from Mull, and one from Ardnamurchan. The Mull samples; a gabbro emplaced during the main phase of intrusion (ML5), and the youngest pluton, the Loch Ba Felsite (ML3) (Emeleus & Bell 2005), yielded ZHe ages that are indistinguishable, with a mean age of 58.0 ± 0.4 Ma (Table 1). A ZHe age of 55.9 ± 3.4 Ma was determined from the youngest pluton from Ardnamurchan, the Centre 3 quartz monzonite (AR13). The Mull zircons have consistent strong sector zonation in CL, and the Ardnamurchan zircons appear to be homogeneous, therefore suggesting that the F_T-corrected ages correctly quantify α-ejection.

The AFT ages from these samples (60.2 ± 5.1 Ma ML3, 59.5 ± 6.1 Ma ML5 and 59.1± 7.0 Ma AR13), and an additional sample from Ardnamurchan (AR2, a mid-sequence gabbro, AFT age 57.2 ± 6.4 Ma), are younger, but within error of the ZHe ages. All the low temperature thermochronology is within error of published zircon U-Pb ages (58.5 ± 0.1 Ma; in Emeleus & Bell 2005) at the 1σ level. No confined fission tracks were observed in the four samples, and pervasive fluid inclusions prevented AHe analyses. The U-Pb, ZHe and AFT ages suggests that the Mull and Ardnamurchan central complexes experienced rapid cooling from ~900ºC to temperatures of less than 100°C within a few Myr, immediately after the cessation of intrusive activity (Fig 5A, B).

Rum

Pegmatitic veins from the Western Layered Series (R11) were analysed using all three thermochronometers, and a multi-crystal aliquot ZHe age was also obtained from the Western Granite (SR131). The ZHe ages from both plutons are indistinguishable, and the three aliquots yield a mean ZHe age of 54.6 ± 1.9 Ma (Table 1), slightly younger than the crystallization age (60.53 ± 0.05 Ma; Hamilton *et al.* 1998). R11 yielded an AFT age of 58.6 ± 6.6 Ma (Table 3), within error of the ZHe and crystallization ages, and has a mean track length of 13.6 ± 1.7 μm (Table 3, Fig. 4 insert). Although there are very few confined tracks (n=26), the short lengths are significant as this sample is known to have been within a few 100 m of the surface at 60 Ma, and is thought to have remained there throughout the Cenozoic (Fig. 2) (Emeleus 1985; Emeleus 1997; Troll *et al.* 2008). The mean track length and track length distribution are similar to those from Skye reported by Lewis *et al.* (1992) (Fig. 4). The measured AHe age obtained from this sample is 27.2 ± 1.6 Ma. Approximately 75% of R11 apatites exhibit ~15 μm wide U-rich rims, with an enrichment factor of ~2, and zoned apatites were generally of better quality with fewer inclusions than non-zoned examples. It is probable that zoned apatites were selected for (U-Th)/He analysis, and uncorrected AHe ages and zoned apatites were used in the subsequent modelling.

Forward modelling using the known geological constraints for the Rum Central Complex predicts R11 should have a mean track length of 14.5 ± 1.07 μm, and a measured AHe age of ~ 40 Ma. Although it is not possible to perform rigorous inverse modelling (as this requires 100 tracks), the shorter lengths and younger AHe age suggest this sample has experienced a more complex thermal history. The thermal histories that allow track shortening without significant AFT age reduction are limited and within the envelope of acceptable thermal histories three general forms of t-T path are possible (Fig. 4B): 1) initial cooling is followed by an immediate rapid re-heating event (80°C < T_{max} < 180°C) and slow cooling; 2) initial cooling is followed by a gradual reheating to T_{max} (40-90 °C) for 10-25 Myr; and 3) initial cooling is followed by a short duration reheating event at ~45-50 Ma. The possible thermal histories produced by inverse modelling of the ZHe, AFT and AHe data from R11 are also shown for comparison (Fig. 4B). There is no field evidence for the 1-3 km of sedimentary or volcanic cover that is required for type 1 and type 2 thermal histories. Indeed, the nearby Skye and Eigg Lava Fields were deeply eroded and incised by 58 Ma (Fig. 2) (Emeleus 1997). Although younger volcanic units may have existed, they are likely to have been rapidly eroded. Forward modelling of t-T paths suggest that while the data are limited, cooling histories with long residence at near surface temperatures perturbed by a short (< 1-5 Myr) reheating event at ~45-50 Ma (option 3) best fit the data (Fig 4, 5C).

Skye

ZHe ages were obtained from the oldest, and one of the youngest plutons from the Skye Central Complex. Pegmatitic veins within the outer Cuillins Gabbro (SC1/2) yield a mean ZHe age of 61.0 ± 2.3 Ma, within error of the U-Pb zircon crystallization age obtained from the same aliquots (58.91 ± 0.18 Ma; Hamilton *et al.* 1998). Single crystal ZHe age determinations show no variation with crystal size (effective radius of 35-75 µm, i.e. T_C range from 190-205ºC), suggesting rapid cooling. CL images showed sector zonation implying that applying a homogeneous F_T correction is valid. ZHe ages from the younger Eastern Red Hills complex show greater variation. The Beinn an Dubhaich granite (BnD & GP422) yields a mean ZHe age of 62.6 ± 1.8 Ma, slightly older than the U-Pb age of 55.89 ± 0.18 Ma (Emeleus & Bell 2005). Low yields prevented CL imaging, but the magnitude of the age discrepancy could be achieved with subtle to moderate U-Th zonation. An AFT age of 61.2 ± 7.2 Ma (within error of the crystallization age) and a single uncorrected AHe age of 35.8 ± 2.0 Ma were also obtained from the Glamaig granite, a mid sequence pluton from the Western Red Hills (SK3, Table 2 & 3). The lack of replication of the AHe age means the data cannot be rigorously interpreted.

The ZHe and AFT ages of the Skye Central Complex are generally consistent with the geological evidence for rapid exhumation of the early plutons e.g. SC1/2 (Fig. 2), and with the ages predicted from the modelled cooling of the plutonic complex (Fig. 3). The agreement between the ZHe and AFT data at localities across the complex suggests that the entire complex had cooled below temperatures of ~100ºC a few Myr after emplacement ceased at ~55 Ma (Fig. 5D).

ZHe, AFT and AHe analyses were also performed on samples SK4 & SK6, from the Marscoite suite a narrow (< 50 m) arcuate unit that was emplaced as a ring dyke along a caldera-bounding fault (Emeleus & Bell 2005). It marks the end of activity in the Western Red Hills, and records a different low temperature thermal history. There is significant variation in ZHe age (Table 1.), consistent with the highly variable oscillatory CL zonation observed in these samples. Ignoring aliquots where measured ZHe ages can be attributed to extreme zonation (ZHe > U-Pb age), the mean F_T corrected ZHe age of this sample is 60.2 ± 2.6 Ma, close to the estimated crystallization age of ~58 Ma. The AFT age of SK4 is 47.8 ± 3.0 Ma, significantly younger than the SK3 Glamaig Granite sample (although this is less apparent at 2σ). A distance of less than 3 km separates the Glamaig and Marsco samples. SK4 yielded a mean AHe age of 32.8 ± 4.9 Ma n=5 (uncorrected), and forward modelling suggests that both the AFT data and AHe ages require a short duration reheating followed by rapid cooling from 120-180ºC to near surface temperatures (≤ 40ºC) at 47-45 Ma (Fig. 5E).

Discussion

Palaeogene cooling in the HIP

The low temperature thermochronology data presented here supports rapid cooling on both a local (Central Complex) and province scale (Fig. 5). The zircon (U-Th)/He analyses from all four HIP central complexes yield a mean age of 59.4 ± 3.3 Ma (1σ, n=18). This is within error of the mean AFT age of 59.3 ± 3.4 Ma, and although there are large uncertainties on the individual AFT ages, the consistency of the AFT ages across the region supports a Palaeogene cooling signal. The agreement between published U-Pb and ^{40}Ar-^{39}Ar, and our ZHe and AFT ages suggests that plutonic cooling to near surface temperatures (< 80ºC) was rapid (> 200ºC/Myr), and occurred immediately after the cessation of magmatic activity at 58-55 Ma.

The AFT and ZHe data appear to be inconsistent with the published ZFT ages (mean age of 50.6 ± 4.7 Ma, Lewis *et al.* 1992), although at 2σ this would be less apparent. U-Th zonation in the zircons cannot account for the observed age disparity between the ZHe and ZFT datasets, and while it is possible that the large errors in the AFT data, caused by the low U concentrations, mask additional complexity it is difficult to reconcile these with the young ZFT ages reported by Lewis *et al.* (1992). It is possible to have complete annealing of fission tracks with only partial loss of helium by diffusion during short duration pulsed heating events (Reiners 2009). This can explain age inversion between the fission track and (U-Th)/He applied to an individual mineral phase, but even rapid pulsed heating cannot cause the age inversion between ZFT ages and AFT ages (Reiners 2009). The accumulation of radiation damage over several 100 Myr of accumulation for typical U and Th concentrations can effect annealing and He diffusion in both apatite and zircon (Ehlers *et al.* 2005; Flowers *et al.* 2009) and can also cause age inversion. However, the very low concentrations of U and Th in the HIP apatites and zircons in this study do not support such a mechanism.

The simplistic thermal modelling (Fig. 3) suggests that, unless intrusion continued for several Myr, the Central Complexes should have cooled to ambient crustal temperatures within ~3 Myr, and the extensive hydrothermal convection would further accelerate the cooling. Independent estimates suggest ambient temperatures of 50ºC (Thrasher 1992) or less (Holness & Fallick 1997; Troll *et al.* 2000; Bell &

Williamson 2002) depending on the timing of denudation. The ZHe and AFT data of this study is consistent with this model, and we suggest that it is not possible to resolve a separate denudation driven cooling event; i.e. denudation occurred within a few Myr of final emplacement. Cooling and denudation at ~59 Ma correlates well with peak sedimentation in offshore fan sequences (White & Lovell 1997). The lack of replicating AHe data from the major plutons prevents better constraint of the amount and distribution of this denudation.

Mid-Eocene thermal perturbations in the HIP

Given the record of province wide Palaeogene cooling, the AFT and AHe data from SK4 on Skye (and R11, Rum) requires a post-Palaeogene thermal event (Fig. 5), most probably in the mid-Eocene. Complete resetting of AFT ages and shortening of fission track lengths is usually observed in samples that have experienced reheating, but the highly localised nature of the reheating event on Skye, and the absence of post-Palaeogene volcanic or sedimentary cover imply that burial is not a viable mechanism. Perturbation of crustal temperatures as a result of later intrusions; either directly, or by rejuvenation of hydrothermal activity must therefore be considered. No early- to mid-Eocene intrusions have been identified in the HIP, however there has been very little dating of the multiple generations of Tertiary dykes, and the existence of small volume mid-Eocene intrusions either on the surface or at depth cannot be precluded. However, the absence of large volume mid-Eocene intrusions, and the regional ~60 Ma AFT cooling age makes the operation of a large, long-lived magmatic system unlikely.

The mid-Eocene event that affects the Marscoite suite correlates well with the reported AFT cooling ages from the country rocks surrounding the central complex (Lewis *et al.* 1992). From cross-cutting field relationships the Marscoite suite was emplaced at ~58 Ma, and in part bounds the Glamaig granite, separating it from the country rocks, yet the Glamaig granite AFT ages support Palaeogene cooling. We suggest that relatively small-volume shallow-level emplacement rejuvenated the hydrothermal system in the mid-Eocene and exploited existing structural weaknesses as flow pathways. Pulsed hydrothermal activity was proposed by Taylor & Forrester (1971, 1977), and convective transport would be focussed along the structural boundary of the Marscoite suite and so the thermal effects may not penetrate the neighbouring granite. The AFT data presented by Lewis *et al.* (1992) show significant length shortening and ~ 47 Ma ages in samples from north and east of the Skye Central Complex. Although no samples were taken from the country rocks in contact with the Marscoite suite, the mid-Eocene cooling ages in the country rocks suggest that the heat source may have been sufficiently large and shallow to rejuvenate the hydrothermal system surrounding the complex. The distribution of AFT ages and track lengths in the country rocks does not constrain the spatial extent of the mid-Eocene hydrothermal system, but short mean track lengths suggests that additional, younger thermal perturbations (T_{max} < 90°C) may have occurred (Fig. 5). The mid-Eocene event may therefore not be the final thermal event to affect the Skye Central Complex, but it may be the last to drive hydrothermal activity at temperatures in excess of 120°C.

The thermal modelling and geological constraints for the Rum data suggests a similar scenario, with small volume intrusion driving localised convective transfer of heat through near surface samples, possibly through hydrothermal activity. The pegmatitic veins of the Rum may also have acted as preferential fluid pathways, but this cannot be corroborated because of the lack of apatite in the host ultramafic units. The country rocks surrounding the Rum Central Complex yielded no apatite, so the affect of any hydrothermal activity cannot be determined. The thermal maximum of the reheating event on Rum was likely lower than that recorded on Skye, reaching no more than 80-90°C. Forward modelling does not preclude later thermal pulses of similar or lower temperature (Fig. 5).

The AFT ages from Ardnamurchan and Mull reflect the regional rapid Palaeogene cooling trend, but lack of track length and AHe data prevents further analysis. Like the Marscoite suite on Skye, the Loch Ba Felsite (ML3) was emplaced along caldera bounding faults, and the Palaeogene AFT age for this sample therefore suggests that if mid-Eocene intrusion rejuvenated the hydrothermal system here, T_{max} was < 90ºC.

Rejuvenation mechanisms and the influence of the Iceland plume

The onset of continental rifting at ~55 Ma correlates with a reduction in the areal extent of magmatic activity, and rifting is generally thought to have deprived the HIP and the European continental shelf of melts (Saunders *et al.* 1997). However, mid-Eocene magmatism is not unknown on the European margin. At Loch Roag, on the Isle of Lewis, a kimberlite-like dyke containing mantle xenoliths has been dated at 45.16 ± 0.02 Ma (Upton pers. com.), and in western Ireland a suite of dolerite dykes were emplaced between 40 and 50 Ma (Kirstein & Timmerman 2000). These small volume intrusions are approximately coeval with the thermal anomaly we have identified in the HIP. On the Greenland margin widespread lithosphere-derived magmatism is roughly contemporaneous (50-47 Ma) but is associated with the margin passing over the axis of the proto-Iceland plume (Bernstein *et al.* 1998; Storey *et al.* 2004; Tegner *et al.* 2008). An episode of voluminous basaltic volcanism in the Rockall Trough during the Eocene suggests that fertile mantle may have melted beneath the European margin at this time (O'Connor *et al.* 2000), and the lateral transport of even small volume melts could have triggered the magmatism observed in Ireland and at Loch Roag (and inferred for the HIP): either by emplacement of the fresh mantle material, or by remobilisation above a renewed mantle thermal anomaly.

The European margin experienced significant re-organisation of the stress regime in the Eocene with the rifting of the North Atlantic competing against the far field effects of the Alpine orogeny. A marked decrease in the relative convergence rate between Europe and Africa occurred from the Palaeocene to the Early Eocene, and corresponds to peak magmatism and rifting in the North Atlantic (Rosenbaum *et al.* 2002). Reactivation of ancient structures has occurred throughout the rifting of the North Atlantic (see review in Hansen *et al.* 2009), and further re-organisation of the stress regime during the Eocene may have allowed remobilisation and shallow level emplacement of small volume lithospheric melts in the HIP. If stress field reorganisation controlled rejuvenation, the thermal event is likely to be spatially limited, focussed along the traces of ancient crustal structures.

In the HIP the rejuvenation appears to be associated with the structural control of the central complexes, implying preferential reactivation of the Palaeogene volcanic conduits. This reactivation of volcanic complexes has not been identified previously because few low temperature thermochronology studies consider volcanic suites.

Conclusions

We have shown that low temperature thermochronology is uniquely suited for the identification of the full extent of magmatic activity in Large Igneous Provinces, and have constrained a two stage cooling history of the HIP. Zircon (U-Th)/He and apatite fission track analyses from major plutons in all Central Complexes of the HIP constrain regional rapid cooling to near surface temperatures. This cooling event is indistinguishable from published crystallization ages, and is consistent with the known geological constraints. However, additional samples from small volume, structurally controlled intrusions have identified mid-Eocene thermal events in the HIP, and we can infer a somewhat enigmatic phase of post-rifting magmatism that has previously been overlooked. Although the LTT identifies the effects of this magmatism, in the HIP, the magmatic products themselves remain unidentified. We suggest that this Mid-Eocene intrusion was in response to the competition between extension in the proto-North Atlantic, the effects of the Iceland plume, and far field compression ahead of the Alpine orogeny.

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References

Balestrieri, M. L., Stuart, F. M., Persano, C., Abbate, E., & Bigazzi, G., 2005. Geomorphic development of the escarpment of the Eritrean margin, southern Red Sea from combined apatite fission-track and (U-Th)/He thermochronometry. *Earth and Planetary Science Letters*, **231**: 97-110.

Bell, B. R., & Harris, J. W., 1986. *An excursion guide to the geology of the Isle of Skye*. Geological Society of Glasgow.

Bell, B. R., & Williamson, I. T., 2002. Tertiary Igneous Activity. *In*: Trewin, N. H. (Ed.), *The Geology of Scotland*. Geological Society, London, London. 371-430.

Bell, J. D., 1966. Granites and associated rocks of the eastern part of the Western Red Hills Complex, Isle of Skye. *Transactions of the Royal Society of Edinburgh*, **66**: 307-343.

Bell, J. D., 1976. The Tertiary intrusive complex on the Isle of Skye. *Proceedings of the Geological Association*, **87**: 247-271.

Bernstein, S., Kelemen, P. B., Tegner, C., Kurz, M. D., Blusztajn, J., & Brooks, C. K., 1998. Post-breakup basaltic magmatism along the East Greenland Tertiary rifted margin. *Earth and Planetary Science Letters*, **160**: 845-862.

Brown, D. J., & Bell, B. R., 2006. Intrusion-induced uplift and mass wasting of the Palaeogene volcanic landscape of Ardnamurchan, NW Scotland. *Journal of the Geological Society, London*, **163**.

Brown, D. J., Holohan, E. P., & Bell, B. R., 2009. Sedimentary and volcano-tectonic processes in the British Paleocene Igneous Province: a review. *Geological Magazine*, **146**: 326-352.

Brown, R. W., Summerfield, M. A., & Gleadow, A. J. W., 1994. Apatite fission track analysis: Its potential for the estimation of denudation rates and implications for models of long-term landscape development. *In*: Kirkby, M. J. (Ed.), *Process Models and Theoretical Geomorphology*. John Wiley, New York. 23-53.

Bryan, S. E., Riley, T. R., Jerram, D. A., Stephens, C. J., & Leat, P. T., 2002. Silicic volcanism: An undervalued component of large igneous provinces and volcanic rifted margins. *Geological Society of America Special Papers*, **362**: 97-118.

Chambers, L. M., 2000. Age and duration of the British Tertiary Igneous Province: implications for the development of the ancestral Iceland plume University of Edinburgh.

Chambers, L. M., & Pringle, M. S., 2001. Age and duration of activity at the Isle of Mull Tertiary igneous centre, Scotland, and confirmation of the existence of subchrons during Anomaly 26r. *Earth and Planetary Science Letters*, **193**: 333-345.

Chambers, L. M., Pringle, M. S., & Parrish, R. R., 2005. Rapid formation of the Small Isles Tertiary centre constrained by precise ^{40}Ar/^{39}Ar and U-Pb ages. *Lithos*, **79**: 367-384.

Clift, P. D., Lin, J., & Odp Leg 184 Scientific, P., 2001. Patterns of extension and magmatism along the continent-ocean boundary, South China margin. *In*: Wilson, R. C. L., Whitmarsh, R. B., Froitzheim, N., and Taylor, B. (Eds.), *Non-Volcanic rifting of continental margins: A comparison of evidence from land and sea*. Special Publications. Geological Society, London. 489-510.

Coffin, M. F., & Eldholm, O., 1994. Large Igneous Provinces - Crustal Structure, Dimensions, and External Consequences. *Reviews of Geophysics*, **32**: 1-36.

Corfu, F., Hanchar, J. M., Hoskin, P. W. O., & Kinny, P., 2003. Atlas of zircon textures. *In*: Hanchar, J. M., and Hoskin, P. W. O. (Eds.), *Zircon*. Reviews in Mineralogy and Geochemistry. Mineralogical Society of America. 468-500.

Dobson, K. J., 2006. The zircon (U-Th)/He thermochronometer: development and application of thermochronometers in igneous provinces, University of Glasgow.

Dobson, K. J., Persano, C., & Stuart, F. M., 2009. Quantitative constraints on mid- to shallow crustal processes using the zircon (U-Th)/He thermochonometer. *In*: Lisker, F., Ventura, B., and Glasmacher, U. A. (Eds.), *Thermochronological methods: from palaeotemperature constraints to landscape evolution models*. Geological Society of London, Special Publications. **324.** . 47-56.

Dobson, K. J., Stuart, F. M., Dempster, T. J., & EIMF, 2008. U and Th zonation in Fish Canyon Tuff zircons: Implications for a zircon (U–Th)/He standard. *Geochimica et Cosmochimica Acta*, **72**: 4745–4755.

Donelick, R. A., & Miller, D. S., 1991. Enhanced TINT fission-track densities in low spontaneous track density apatites using Cf-252 derived fission fragment tracks - a model and experimental observations. *Nuclear Tracks and Radiation Measurements*, **18**: 301-307.

Ehlers, T. A., Chaudhri, T., Kumar, S., Fuller, C. W., Willett, S. D., Ketcham, R. A., Brandon, M. T., Belton, D. X., Kohn, B. P., Gleadow, A. J. W., Dunai, T. J., & Fu, F. Q., 2005. Computational tools for low-temperature thermochronometer interpretation. *In*: Reiners, P. W., and Ehlers, T. A. (Eds.), *Thermochronology*. Reviews in Mineralogy and Geochemistry. Mineralogical Society of America 589-622.

Emeleus, C. H., 1973. Granophyre pebbles in Tertiary conglomerates on the Isle of Canna, Inverness-shire. *Scottish Journal of Geology*, **9**: 157-159.

Emeleus, C. H., 1982. The Central Complexes. *In*: Sutherland, D. S. (Ed.), *Igneous Rocks of the British Isles*. John Wiley & Sons Ltd. 369-414.

Emeleus, C. H., 1985. The Tertiary lavas and sediments of Northwest Rhum, Inner Hebrides. *Geological Magazine*, **122**: 419-437.

Emeleus, C. H., 1997. *Geology of Rum and the adjacent islands*, **Sheet 60 (Scotland)**. Memoir of the British Geological Survey.

Emeleus, C. H., & Bell, B. R., 2005. *The Palaeogene volcanic districts of Scotland*. British Regional Geology. British Geological Survey

Emeleus, C. H., Wadsworth, W. J., & Smith, N. J., 1985. The early igneous and tectonic history of the Rhum Tertiary Volcanic Center. *Geological Magazine*, **122**: 451-457.

Flowers, R. M., Ketcham, R. A., Shuster, D. L., & Farley, K. A., 2009. Apatite (U-Th)/He thermochronometry using a radiation damage accumulation and annealing model. *Geochimica et Cosmochimica Acta*, **73**: 2347-2365.

Foeken, J. P. T., Stuart, F. M., Dobson, K. J., Persano, C., & Vilbert, D., 2006. A diode laser system for heating minerals for (U-Th)/He chronometry. *Geochemistry Geophysics Geosystems*.

Forester, R. W., & Taylor, J., Hugh P., 1976. ^{18}O-depleted igneous rocks from the Tertiary complex of the Isle of Mull, Scotland. *Earth and Planetary Science Letters*, **32**: 11-17.

Fyfe, J. A., Long, D., & Evans, D., 1993. *United Kingdom offshore regional report: the geology of the Malin-Hebrides sea area*. London: HMSO for the British Geological Survey.

Gleadow, A. J., & Brown, R. W., 2000. Fission track thermochronology and the long term denudation response to tectonics. *In*: Summerfield, M. A. (Ed.), *Geomorphology and Global Tectonics*. John Wiley & Sons Ltd. 57-75.

Hamilton, M. A., Pearson, D. G., Thompson, R. N., Kelley, S. P., & Emeleus, C. H., 1998. Rapid eruption of Skye lavas inferred from precise U-Pb and Ar- Ar dating of the Rum and Cuillin plutonic complexes. *Nature*, **394**: 260-263.

Hansen, J., Jerram, D. A., McCaffrey, K., & Passey, S. R., 2009. The onset of the North Atlantic Igneous Province in a rifting perspective. *Geological Magazine*, **146**: 309-325.

Harker, A., 1904. *The Tertiary igneous rocks of Skye*, **Scotland Sheets 70 and 71**. Memoirs of the Geological Survey.

Holness, M. B., 1999. Contact metamorphism and anatexis of Torridonian arkose by minor intrusions of the Rum Igneous Complex, Inner Hebrides, Scotland. *Geological Magazine*, **136**: 527-542.

Holness, M. B., & Fallick, A. E., 1997. Palaeohydrology of the calcsilicate aureole of the Beinn an Dubhaich granite, Skye: a stable isotopic study. *Journal Of Metamorphic Geology*, **15**.

Holness, M. B., & Isherwood, 2003. The aureole of the Rum Tertiary Igneous Complex, Scotland. *Journal of the Geological Society, London*, **160**: 15-27.

Holohan, E. P., Troll, V. R., Errington, M., Donaldson, C. H., Nicoll, G. R., & Emeleus, C. H., 2009. The Southern Mountains Zone, Isle of Rum, Scotland: volcanic and sedimentary processes upon an uplifted and subsided magma chamber roof. *Geological Magazine*, **146**: 400-418.

Hourigan, J. K., Reiners, P. W., & Brandon, M. T., 2005. U-Th zonation-dependent alpha-ejection in (U-Th)/He chronometry. *Geochimica et Cosmochimica Acta*, **69**: 3349-3365.

Hurford, A. J., & Green, P. F., 1982. A users guide to fission track dating calibration. *Earth and Planetary Science Letters*, **59**: 343-354.

Jolley, D. W., 1997. Palaeosurface palynofloras of the Skye lava field and the age of the British Tartiary volcanic province. *In*: Widdowson, M. (Ed.), *Palaeosurfaces: Recognition, Reconstruction and Palaeoenvironmental Interpretation*. Geological Society, London. Special Publications, London. 67-94.

Jolley, D. W., Bell, B. R., Williamson, I. T., & Prince, I., 2009. Syn-eruption vegetation dynamics, paleosurfaces and structural controls on lava field vegetation: An example from the Palaeogene Staffa Formation, Mull Lava Field, Scotland. *Review of Palaeobotany and Palynology*, **153**: 19-33.

Jones, S. M., White, N., Clarke, B. J., Rowley, E., & Gallagher, K., 2002. Present and past influence of the Iceland plume on sedimentation. *In*: Dore, A. G., Cartwright, J. A., Stoker, M. S., Turner, J. P., and White, N. (Eds.), *Exhumation of the North Atlantic margin: Timing, mechanisms and implications for petroleum exploration* Special Publication. Geological Society, London, London. 13-25.

Kerr, A. C., 1995. The geochemical stratigraphy, field relations and temporal variation of the Mull-Morvern Tertiary lava succession, NW Scotland. *Transactions of the Royal Society of Edinburgh*, **86**: 35-47.

Kirstein, L. A., & Timmerman, M. J., 2000. Evidence of the proto-Iceland plume in northwestern Ireland at 42 Ma from helium isotopes. *Journal of the Geological Society*, **157**: 923-927.

Kohn, B. P., Gleadow, A. J. W., Brown, R., Gallagher, K., Lorencak, M., & Noble, W. P., 2005. Visualizing thermotectonic and denudation histories using apatite fission track thermochronology. *In*: Reiners, P. W., and Ehlers, T. A. (Eds.), *Thermochronology*. Reviews in Mineralogy and Geochemistry. Mineralogical Society of America 527-565

Lewis, C. L. E., Carter, A., & Hurford, A. J., 1992. Low-temperature effects of the Skye Tertiary intrusions on Mesozoic sediments in the Sea of Hebrides Basin *In*: Parnell, J. (Ed.), *Basins on the Atlantic Seaboard: Petroleum Geology, Sedimentology and Basin Evolution* Special Publication. Geological Society, London 175-188.

Monani, S., & Valley, J. W., 2001. Oxygen isotope ratios of zircon: magma genesis of low delta O-18 granites from the British Tertiary Igneous Province, western Scotland. *Earth and Planetary Science Letters*, **184**: 377-392.

Nadin, P. A., Kusznir, N. J., & Toth, J., 1995. Transient regional uplift in the early Tertiary of the Northern North-Sea and the development of the Iceland plume. *Journal of the Geological Society, London*, **152**: 953-958.

Nicoll, G. R., Holness, M. B., Troll, V. R., Donaldson, C. H., Holohan, E. P., Emeleus, C. H., & Chew, D., 2009. Early mafic magmatism and crustal anatexis on the Isle of Rum: evidence from the Am Mam intrusion breccia. *Geological Magazine*, **146**: 368-381.

O'Connor, J. M., Stoffers, P., Wijbrans, J. R., Shannon, P. M., & Morrissey, T., 2000. Evidence from episodic seamount volcanism for pulsing of the Iceland plume in the past 70 Myr. *Nature*, **408**: 954-958.

Pearson, D. G., Emeleus, C. H., & Kelley, S. P., 1996. Precise ^{40}Ar/^{39}Ar age for the initiation of Palaeogene volcanism in the Inner Hebrides and its regional significance. *Journal of the Geological Society, London*, **153**: 815-818.

Persano, C., Barfod, D. N., Stuart, F. M., & Bishop, P., 2007. Constraints on early Cenozoic underplating-driven uplift and denudation of western Scotland from low temperature thermochronometry. *Earth and Planetary Science Letters*, **263**: 404-419.

Persano, C., Bishop, P., & Barfod, D. N., 2002. Apatite (U-Th)/He age constraints on the development of the Great Escarpment on the southeastern Australian passive margin. *Earth and Planetary Science Letters*, **200**: 79-90.

Persano, C., Stuart, F. M., Bishop, P., & Dempster, T. J., 2005. Deciphering continental breakup in eastern Australia using low-temperature thermochronometers. *Journal of Geophysical Research-Solid Earth*, **110**.

Pik, R., Marty, B., Carignan, J., & Lave, J., 2003. Stability of the Upper Nile drainage network (Ethiopia) deduced from (U-Th)/He thermochronometry: implications for uplift and erosion of the Afar plume dome. *Earth and Planetary Science Letters*, **215**: 73-88.

Reiners, P. W., 2009. Nonmonotonic thermal histories and contrasting kinetics of multiple thermochronometers. *Geochimica et Cosmochimica Acta*, **73**: 3612-3629.

Richey, J. E., 1935. *Scotland: the Tertiary Volcanic Districts*. HMSO, Edinburgh.

Rosenbaum, G., Lister, G. S., & Duboz, C., 2002. Relative motions of Africa, Iberia and Europe during Alpine orogeny. *Tectonophysics*, **359**: 117-129.

Saunders, A. D., Fitton, J. G., Kerr, A. C., Norry, M. J., & Kent, R. W., 1997. The North Atlantic Igneous Province. *In*: Mahoney, J. J., and Coffin, M. F. (Eds.), *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*. American Geophysical Union, Washington DC. 45-93.

Saunders, A. D., Jones, S. M., Morgan, L. A., Pierce, K. L., Widdowson, M., & Xu, Y. G., 2007. Regional uplift associated with continental large igneous provinces: The roles of mantle plumes and the lithosphere. *Chemical Geology*, **241**: 282-318.

Smith, N. J., 1985. The age and structural setting of limestones and basalts on the Main Ring Fault in SE Rhum. *Geological Magazine*, **122**: 439-445.

Spotila, J. A., 2005. Applications of low-temperature thermochronometry to quantification of recent exhumation in mountain belts. *In*: Reiners, P. W., and Ehlers, T. A. (Eds.), *Thermochronology*. Reviews in Mineralogy and Geochemistry. Mineralogical Society of America 449-466

Stockli, D., 2005. Application of low-temperature thermochronometry to extensional tectonic settings. *In*: Reiners, P. W., and Ehlers, T. A. (Eds.), *Thermochronology*. Reviews in Mineralogy and Geochemistry. Mineralogical Society of America 411-448.

Storey, M., Pedersen, A. K., Stecher, O., Bernstein, S., Larsen, H. C., Larsen, L. M., Baker, J. A., & Duncan, R. A., 2004. Long-lived postbreakup magmatism along the East Greenland margin: Evidence for shallow-mantle metasomatism by the Iceland plume. *Geology*, **32**: 173-176.

Taylor, H. P., & Forester, R. W., 1971. Low-018 Igneous Rocks from Intrusive Complexes of Skye, Mull, and Ardnamurchan, Western Scotland. *Journal of Petrology*, **12**: 465-&.

Taylor, H. P., & Forester, R. W., 1979. Oxygen And Hydrogen Isotope Study Of The Skaergaard Intrusion And Its Country Rocks - Description Of A 55-Million-Year Old Fossil Hydrothermal System. *Journal of Petrology*, **20**: 355-419.

Tegner, C., Brooks, C. K., Duncan, R. A., Heister, L. E., & Bernstein, S., 2008. Ar-40-Ar-39 ages of intrusions in East Greenland: Rift-to-drift transition over the Iceland hotspot. *Lithos*, **101**: 480-500.

Thrasher, J., 1992. Thermal effect of the Tertiary Cuillins Intrusive Complex in the Jurassic of the Hebrides: an organic geochemical study *In*: Parnell, J. (Ed.), *Basins on the Atlantic Seaboard: Petroleum Geology, Sedimentology and Basin Evolution* Special Publication of the Geological Society, London 35-49.

Troll, V. R., Emeleus, C. H., & Donaldson, C. H., 2000. Caldera formation in the Rum Central Igneous Complex, Scotland . *Bulletin of Volcanology*, **62**: 301-317.

Troll, V. R., Nicoll, G. R., Donaldson, C. H., & Emeleus, H. C., 2008. Dating the onset of volcanism at the Rum Igneous Centre, NW Scotland. *Journal of the Geological Society*, **165**: 651-659.

Valley, J. W., & Graham, C. M., 1996. Ion microprobe analysis of oxygen isotope ratios in quartz from Skye granite: Healed micro-cracks, fluid flow, and hydrothermal exchange. *Contributions to Mineralogy and Petrology*, **124**: 225-234.

White, N., & Lovell, B., 1997. Measuring the pulse of a plume within the sedimentary record. *Nature*, **387**: 888-891.

Williamson, I. T., & Bell, B. R., 1994. The Paleocene Lava-Field of West-Central Skye, Scotland - Stratigraphy, Paleogeography and Structure. *Transactions of the Royal Society of Edinburgh*, **85**: 39-75.

Wohletz, K., & Heiken, G., 1991. *Volcanology and Geothermal Energy*. University of California Press.

Figure Captions

Fig. 1. Location map of the Hebridean Igneous Province. Box shows area covered by Fig. 2.

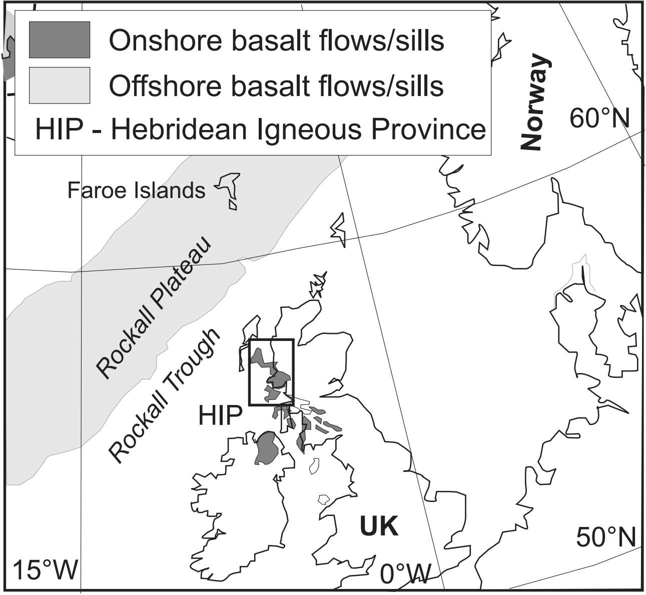
Fig. 2. (A) The major volcanic and plutonic units of the Hebridean Igneous Province. Numbered localities indicate contacts, and units that indicate syn- or post-magmatic uplift, denudation or erosion. Abbreviations and numbers detailed in B. (B) The temporal evolution of the HIP showing stratigraphy, radiometric data (Ages in Ma, to right of stratigraphic column) and temporal distribution of uplift, denudation and other surface processes (approximate timing of events indicated to left of stratigraphic column) (C) Schematic cross sections through the HIP showing relationships between uplift and denudation. Section traces shown in A. Sections are not drawn to scale. HIP lavas overlie a regional unconformity [1, 8, 11, 17, 21], with limited, local late Cretaceous and early Palaeogene deposition [2] (Emeleus & Bell 2005 and refs therein). Lava fields infill the palaeotopography, and the SFL fills and overtops a palaeo-valley system incised into the RCC [15, 16] implying rapid denudation of the RCC after emplacement at ~60.5Ma (Emeleus 1985; Hamilton *et al.* 1998; Chambers *et al.* 2005; Troll *et al.* 2008). Cobbles from the RCC occur in conglomerates beneath and within the SFL on Rum, and Skye. (Clift *et al.* 2001) , implying localised denudation continued during the development of the SLF, at least during eruption hiatuses (Emeleus 1973; Emeleus 1985). Hyaloclastites [3, 17, 22] and sedimentary units [4, 23] intercalated with the SLF & MLF record hiatuses in eruption (Williamson & Bell 1994; Emeleus & Bell 2005). Fluvial conglomerates contain clasts of lava, intrusive and country rock lithologies [4, 18, 25] (Emeleus 1973; Bell &

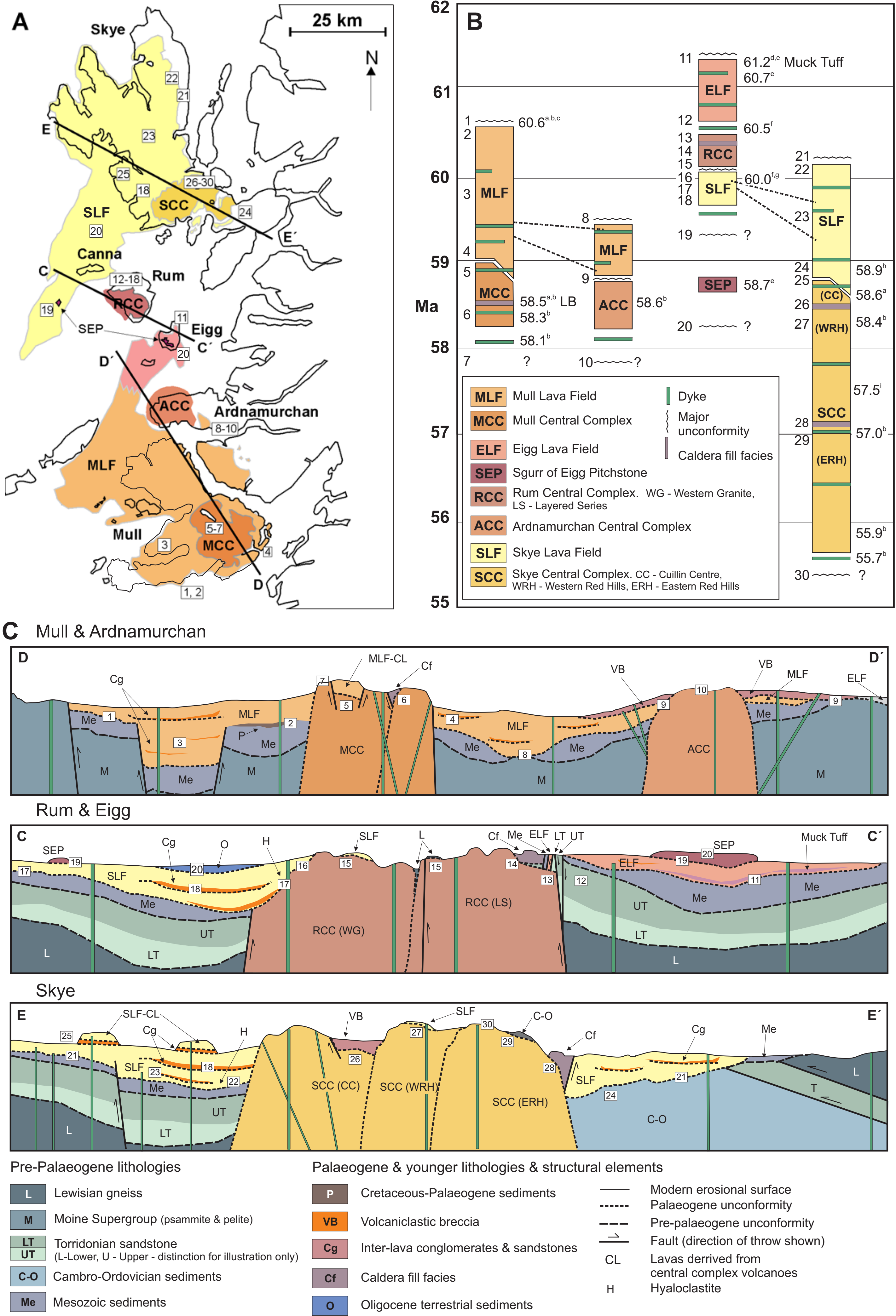
Williamson 2002; Emeleus & Bell 2005) suggesting localised denudation and uplift, and palaeo-canyons had developed prior to eruptions from the Central Complexes [25] (Williamson & Bell 1994). Pollen from sedimentary units in the lava fields indicate multiple phases of uplift and subsidence (of up to 1 km) during the development of the lava fields, that was accompanied by limited regional denudation [3, 23] (Jolley 1997; Jolley *et al.* 2009). Country rocks were domed above the ascending plutons [5, 12, 24] (Emeleus & Bell 2005) , with block uplift and subsidence of up to 1km accommodated by faulting [13, 26] (Emeleus 1982; Emeleus *et al.* 1985; Smith 1985; Holohan *et al.* 2009). Volcaniclastic debris flows triggered by uplift unconformably overlie the MLF, and overstep onto Mesozoic and Moine country rocks [9] (Brown & Bell 2006). Other mass wasting breccias overlie Cuillin phase plutons [26] (Brown *et al.* 2009). In both cases the breccias overlie earlier plutons and dykes, and are cut by intrusions. Active faulting continued throughout emplacement with lavas from the MCC preserved in down-faulted blocks (Kerr 1995). Shallow level emplacement and limited denudation preserves recrystallized roof pendants and fault bounded screens to N and West of RCC [14] (Emeleus 1997), and at both WRH and ERH centres of the SCC [27, 29] (Bell 1966; Bell 1976; Bell & Harris 1986). Later intrusions cross cut ignimbrites and breccias caldera fill facies on Mull, Skye and Rum [6, 13, 28] (Emeleus & Bell 2005; Brown *et al.* 2009; Holohan *et al.* 2009; Nicoll *et al.* 2009). The ELF and SLF were deeply incised before the eruption of the SEP [19] (Emeleus & Bell 2005; Brown *et al.* 2009), but there is no constraint on timing of post-magmatic denudation in the majority of the HIP [7, 10, 30]. In the Canna basin erosion had occurred prior to Oligocene deposition [20] (Fyfe *et al.* 1993). Radiometric ages are taken from: a - Chambers & Pringle (2001), Ar-Ar; b- in Emeleus & Bell (2005) U-Pb; c - in Emeleus & Bell (2005) Ar-Ar; d – Pearson et al. (1996) Ar-Ar, e - Chambers et al. (2005) U-Pb & Ar-Ar; f - Hamilton et al. (1998) U-Pb; g - Troll et al. (2008), Ar-Ar; h – Bell & Williamson (2002), Ar-Ar; i - Chambers (2000), Ar-Ar. (Pearson et al. 1996; Chambers 2000; Chambers & Pringle 2001; Bell & Williamson 2002; Chambers et al. 2005)

Fig. 3. Apatite fission track length data from Skye and Rum. A) Track length histograms from country rocks surrounding the Skye Central Complex, AFT age of reset sample is 49.70 ± 3.80 Ma, AFT age of non-reset sample is 357.12 ± 27.12 Ma (modified from Lewis *et al.* 1992). Dashed lines shows track length histogram for Rum (R11, this study) for comparison. B) Apatite fission track data from Rum, showing the R11 track length histogram (insert) and the forward and inverse modelling results based on AHe, AFT and ZHe data and geological constraints. Box A represents the crystallization age, Box B represents the rapid cooling to near surface temperatures as indicated by the field relationships (see Fig. 2).

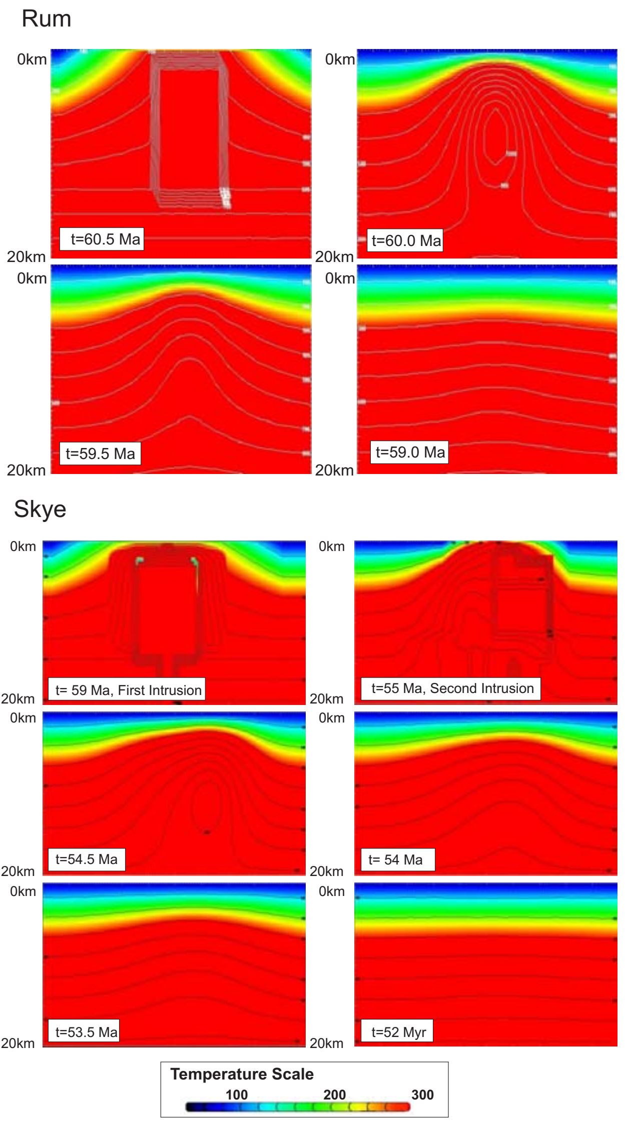
Fig. 4. Plutonic cooling models for the HIP Complexes. Each panel represents a time slices through the Heat 3D simulations (Wohletz & Heiken 1991). Typical thermal properties of country rocks are taken from Carmichael (1984), Fyfe *et al.* (1993) and Ehlers (2005). Models assume no hydrothermal activity and no denudation during cooling. (A) Single pluton of mafic material emplaced into country rock assemblage of 2km basalts overlying a 500m sandstone sedimentary sequence deposited onto a gneissic basement. (B) Multiple intrusions of mafic material emplaced into the same country rock assemblage as (A) but with temporal and spatial separation.

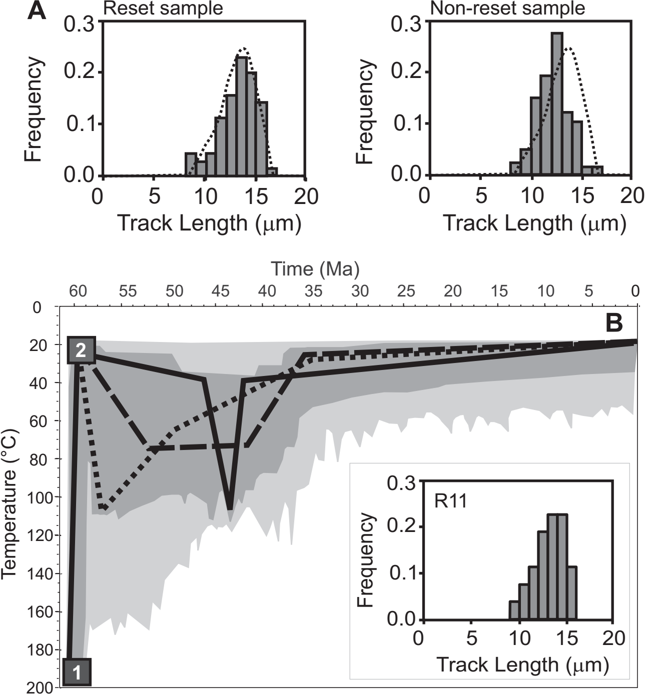
Fig. 5. Schematic cooling histories for the four HIP central complexes. (A) Mull (B) Ardnamurchan (C) Rum (D) Skye. The heavy curve shows model thermal history constrained by field relationships (Fig 2, and black squares), published geochronology (white circles) and thermochronology (this study, black circles). All age data shown with 1σ error bars. ZHe ages from Skye are slightly older than emplacement, and the model thermal history curves reflect the timing of final emplacement. The Skye mid-Eocene peak is only observed in structurally controlled small volume intrusions within the central complex, and in the surrounding country rocks. Fission track length data to support mid-Eocene and potentially later thermal pulses are shown as grey circles FTL this study, FTL[1] Lewis *et al* (1992). Magmatic & thermal events: hatched areas - voluminous eruption, dark grey solid areas - voluminous emplacement. The light grey solid areas represent periods of post-Palaeogene intrusion suggested by the thermochronology data. Solid boundaries - required thermal event with good t-T constraint, dashed boundaries - required thermal event with poor t-T constraint; dotted feint boundaries - possible thermal event.

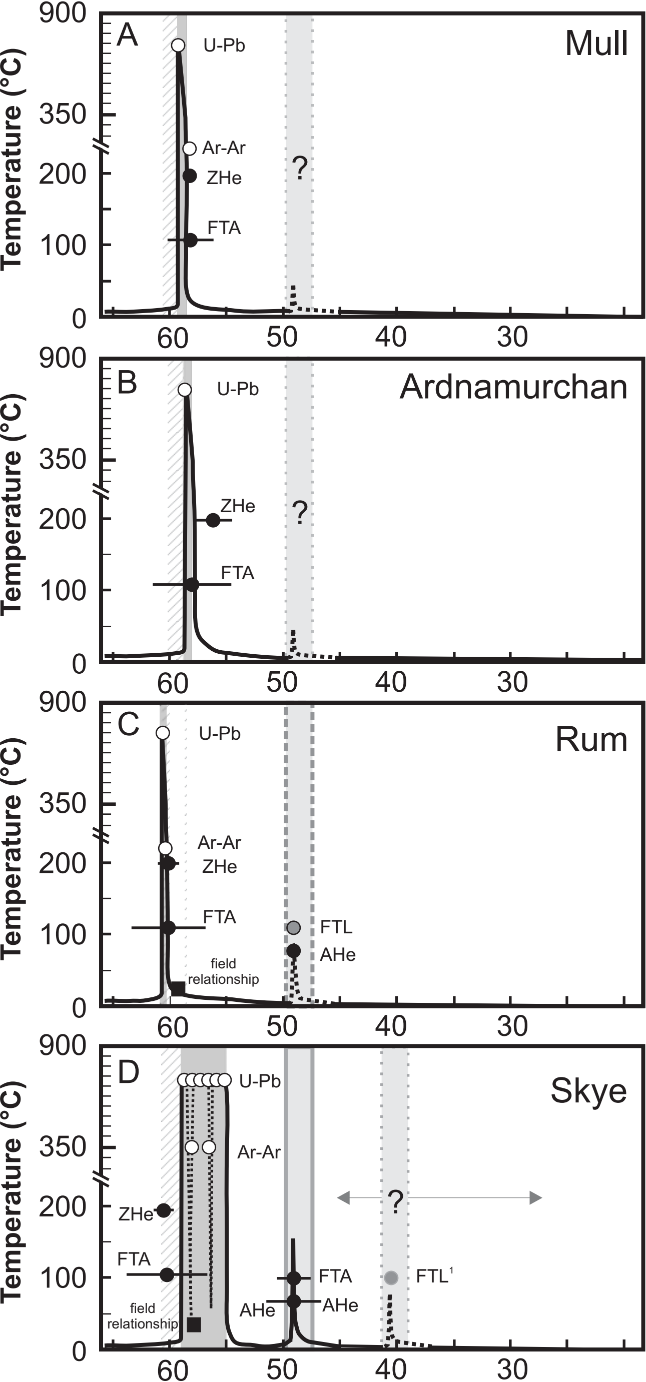

Onshore basalt flows/sills
Offshore basalt flows/sills
HIP - Hebridean Igneous Province
Norway
60°N
Faroe Islands
Rockall Plateau
Rockall Trough
HIP
UK
50°N
15°W
0°W



A
Skye
25 km
N
SLF
SCC
Canna
Rum
RCC
SEP
Eigg
ACC
Ardnamurchan
MLF
Mull
MCC
E
E´
C
C´
D
D´
B
Ma
Muck Tuff
MLF Mull Lava Field
MCC Mull Central Complex
ELF Eigg Lava Field
SEP Sgurr of Eigg Pitchstone
RCC Rum Central Complex. WG - Western Granite, LS - Layered Series
ACC Ardnamurchan Central Complex
SLF Skye Lava Field
SCC Skye Central Complex. CC - Cuillin Centre, WRH - Western Red Hills, ERH - Eastern Red Hills
Dyke
Major unconformity
Caldera fill facies
C
Mull & Ardnamurchan
Rum & Eigg
Skye
Pre-Palaeogene lithologies
L Lewisian gneiss
M Moine Supergroup (psammite & pelite)
LT UT Torridonian sandstone (L-Lower, U - Upper - distinction for illustration only)
C-O Cambro-Ordovician sediments
Me Mesozoic sediments
Palaeogene & younger lithologies & structural elements
P Cretaceous-Palaeogene sediments
VB Volcaniclastic breccia
Cg Inter-lava conglomerates & sandstones
Cf Caldera fill facies
O Oligocene terrestrial sediments
Modern erosional surface
Palaeogene unconformity
Pre-palaeogene unconformity
Fault (direction of throw shown)
CL Lavas derrived from central complex volcanoes
H Hyaloclastite


Rum
0km
20km
t=60.5 Ma
t=60.0 Ma
t=59.5 Ma
t=59.0 Ma
Skye
t= 59 Ma, First Intrusion
t=55 Ma, Second Intrusion
t=54.5 Ma
t= 54 Ma
t=53.5 Ma
t=52 Myr
Temperature Scale
100
200
300


A
Reset sample
Frequency
Track Length (μm)
Non-reset sample
Frequency
Track Length (μm)
Time (Ma)
B
Temperature (°C)
2
1
R11
Frequency
Track Length (μm)



A
Mull
U-Pb
Ar-Ar
ZHe
FTA
?
B
Ardnamurchan
U-Pb
ZHe
FTA
?
C
Rum
U-Pb
Ar-Ar
ZHe
FTA
field relationship
FTL
AHe
D
Skye
U-Pb
Ar-Ar
ZHe
FTA
field relationship
AHe
FTA
AHe
?
FTL¹
Temperature (°C)
900
350
200
100
0
60
50
40
30

Table 1. *Zircon (U-Th)/He data from the Hebridean Igneous Province*

Sample	Location	U (ng)[2]	Th (ng)[2]	He (ncc)	Analytical uncert. (%)	Measured age (Ma)	Recoil correction[3]	Corrected age (Ma)
Skye								
SC1/2 - 1	NG487196	3.00	2.80	25.10	2.2	56.2	0.88	63.9
SC1/2 - 2		0.93	1.04	6.48	2.6	45.2	0.75	60.3
SC1/2 - 3		2.02	2.20	15.50	2.1	50.1	0.86	58.3
SC1/2 - 4		2.66	2.95	21.40	2.1	52.2	0.85	61.4
							Mean ZHe Age	61.0 ± 2.3 Ma
SK4 - 1	NG501258	0.75	1.27	6.20	3.0	48.5	0.77	63.0
SK4 - 3		0.45	0.94	4.36	5.2	53.5	0.75	71.3[a]
SK6 - 1	NG499259	0.71	1.27	5.40	3.3	43.9	0.76	57.8
SK6 - 2[1]		1.11	2.34	11.50	3.2	56.7	0.77	73.6[a]
SK6 - 3[1]		2.35	4.67	17.60	2.8	41.9	0.70	59.9
							Mean ZHe Age	60.2 ± 2.6 Ma
BnD - 1	NG583195	0.52	0.14	3.05	2.8	45.0	0.74	60.8
BnD - 2		0.49	0.25	3.22	7.0	47.8	0.74	64.6
BnD - 3		0.12	0.06	0.78	10.6**	43.2	0.67	63.6
GP422 - 1[1]	NG583195	3.32	2.65	21.50	2.0	45.8	0.73	61.4
							Mean ZHe Age	62.6 ± 1.8 Ma
Mull								
ML5 - 1[1]	NM555373	0.60	0.71	3.28	3.3	35.2	0.61	57.7 ± 3.5 Ma[4]
ML3 - 1	NM582745*	0.42	0.22	2.26	9.5	39.2	0.67	58.5
ML3 - 2		0.36	0.18	1.65	8.1	33.5	0.58	57.8
							Mean ZHe Age	58.2 ± 0.5 Ma
Rum								
SR131 - 1[1]	NM338956	1.49	1.95	8.29	2.5	34.9	0.64	54.5 ± 3.3 Ma[4]
R11 - 1	NM338956	0.51	1.44	4.62	7.8	44.6	0.79	56.5
R11 - 2		0.21	0.48	2.37	3.4	60.0[#]	0.75	80.0
R11 - 3		2.85	2.84	16.90	3.9	39.5	0.75	52.7
R11 - 4		1.27	2.72	1.33	3.3	56.9	0.79	72.2[a]
							Mean ZHe Age	54.5 ± 1.9 Ma
Ardnamurchan								
AR13 - 1[1]	NM683472	1.85	2.43	11.20	1.9	38.0	0.68	55.9 ± 3.4 Ma[4]
Muck								
MT - 1	NM418785	0.24	0.28	1.82	2.1	48.9	0.84^	58.2
MT - 2		3.95	4.30	32.00	1.4	52.8	0.90^	58.7
MT - 3		0.47	0.55	3.96	3.2	54.1	0.95^	56.9
MT - 4		0.60	0.95	5.80	1.4	57.3	0.93^	61.6
MT - 5		2.49	4.08	21.70	1.6	51.5	0.89^	57.9
MT - 6		2.42	3.01	19.90	1.6	52.0	0.88^	59.1
							Mean ZHe Age	58.7 ± 1.8 Ma

Average ZHe ages for the rapidly cooled Muck Tuff (Dobson *et al.* 2009) are shown for comparison. Coordinates given for Ordnance Survey UK National Grid. *grid reference from centre of pluton exact location unknown of sample unknown. [1]Three crystals in aliquot. All other aliquots are single crystals. [2]All samples are blank corrected for Pt foil tubes averages 0.1067 ng ± 14% U and 0.0997 ng ± 14% Th. Low U ** makes greater relative analytical uncertainty on blank. [#] measured age older than crystallization age. [3]α-recoil corrections calculated after Hourigan *et al*. (2005) assuming homogeneous U and Th, except for ^ where true zonation dependant corrections were calculated (Dobson *et al*. 2009). [a] poor age reproducibility a result of variable zonation. [a], ** and [#] aliquots not included in mean age calculations. All ages are shown with 1σ sample specific age reproducibility, except for [4] where age is from single aliquot and age uncertainty is given at ± 6 % (1σ age reproducibility of the Fish Canyon Tuff).

Table 2. *Apatite (U-Th)/He data from the Hebridean Igneous Province*

Sample	Location	U (ng)[2]	Th (ng)[2]	He (ncc)	Analytical uncert. (%)	Measured age (Ma)	Recoil correction[3]	Corrected age (Ma)
Skye								
SK3 - 2	NG513295	0.027	0.098	0.218	3.4	35.8	0.63	56.9± 1.7 Ma[4]
SK4 samples with no inclusions								
SK4 - 1	NG501258	0.013	0.053	0.076	5.9	24.9	0.55	45.3
SK4 - 2		0.012	0.021	0.066	5.4	32.6	0.57	57.1
SK4 - 4		0.013	0.020	0.071	5.2	34.0	0.61	55.7
SK4 - 5		0.020	0.068	0.170	3.0	38.2	0.65	58.8
SK4 - 6*		0.012	0.050	0.098	5.9	34.1	0.63	54.2
					Mean AHe Age	32.8 ± 4.9 Ma		54.2 ± 5.2 Ma
Rum								
R11 - 1	NM338956	0.031	0.062	0.151	2.7	27.2	0.65	41.5± 1.3 Ma[4]

All other samples were of insufficient quality for (U-Th)/He analyses. Coordinates given for Ordnance Survey UK National Grid. All aliquots contained 3 crystals of the same dimensions. [1]F_T calculated assuming homogeneity. *crystals known to contain small monazite inclusions. Sample mean ages shown with 1σ sample specific age reproducibility, except where age is from single aliquot [4] and age uncertainty is given at ± 3 % (1σ age reproducibility Durango apatite).

Table 3. *Apatite fission track data from the Hebridean Igneous Province*

Sample	Location	# Grains	ρ_D ($10^5 cm^{-2}$)	ρ_S ($10^5 cm^{-2}$)	N_S	ρ_i ($10^5 cm^{-2}$)	N_i	P (%)	AFT Age (± 1s)	Dpar (mm) (± 1s)	Mean track Length (mm) (#)	Std Dev ± 1σ
Skye												
SK3	NG513295	21	11.95	0.943	96	3.369	343	100	61.2 ± 7.2	1.73 ± 0.34	-	-
SK4	NG501258	14	10.24	4.391	389	17.259	1529	12.58	47.8 ± 3.0	Not measured	-	-
Mull												
ML3	NM582745*	30	11.52	1.400	200	4.908	701	25.6	60.2 ± 5.1	2.20 ± 0.20	-	-
ML5**	NM555373	22	11.63	1.108	129	3.969	462	100	59.5 ± 6.1	1.82 ± 0.21	-	-
Rum												
R11**	NM338956	25	12.16	0.861	106	3.272	403	97.6	58.6 ± 6.6	2.26 ± 0.28	13.6 ± 0.02 (26)	1.65 ± 0.02
Ardnamurchan												
AR2	NM455693	22	11.63	1.108	129	3.969	462	100	57.2 ± 6.4	1.93 ± 0.23	-	-
AR13	NM683472	22	11.64	1.158	107	4.317	399	99.9	59.1± 7.0	2.01 ± 0.25	-	-

Ages measured by Dr. C. Persano with a zeta of 368 ± 8. All samples were etched for 20 seconds in 5 M HNO_3. All ages are pooled. N_D is 4973 for all samples except SK4 where it is 6368. ** 75 % of the crystals have U rich rims. Coordinates given for Ordnance Survey UK National Grid.